The Non-Linear Complete Absorption Phenomenon for High-Power Microwave in a Plasma Filled Waveguide

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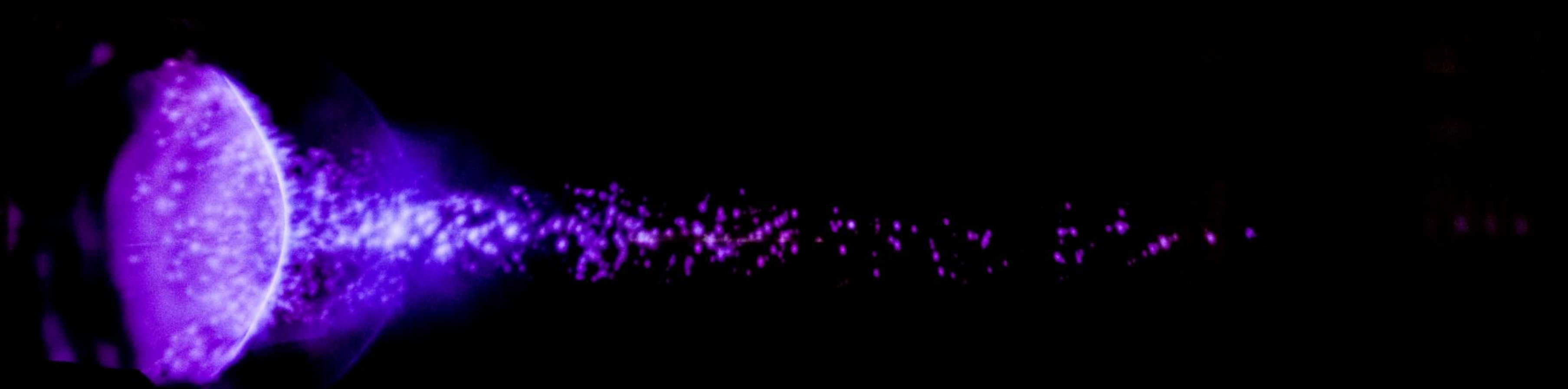

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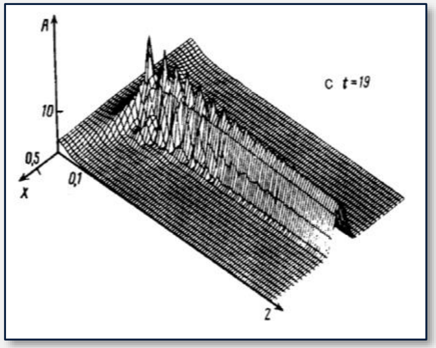
Motivation

Research of phenomena accompanied interaction of ~500 MW, ~0.6 ns, ~10 GHz and ~1200 MW, ~0.6 ns, ~26 GHz microwave beams with neutral gas and preliminary formed plasma

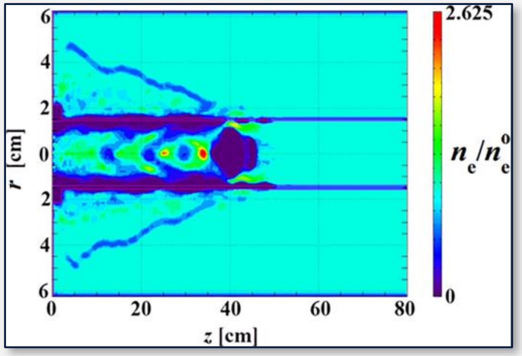
Motivation

- **Ionization-induced channeling**



The ionization-induced channeling (IIC) of an intense microwave beam propagating through neutral gas has been predicted by numerical simulations[1] more than 30 years ago.

- **High-power microwave – driven wakefield**



The feasibility of an experiment to study the effect of HPM-driven wakefield generation in plasma filled waveguide has been analyzed theoretically and simulated[2].

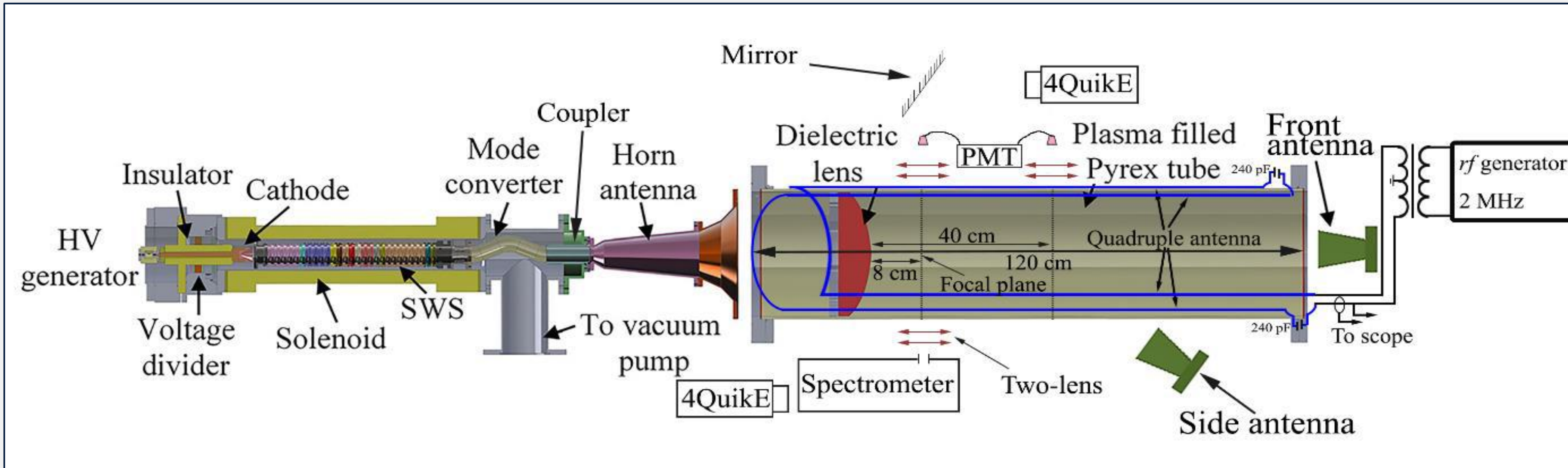
- **Ultra-short (≤1 ns), high power (0.5 – 1.2 GW) microwave (9.7 and 26.6 GHz) Super Radiant Backward Wave Oscillators, are feasible to study the non-linear interaction of high-power microwaves with plasma or neutral gas.**

- **These experiments are the "scaled up" (~ns in time and ~ cm in space) the experiments where powerful extremely short laser pulses (~fs and ~µm) interact with plasma or neutral gas. Diagnostics is expected to be simpler in these time- and spatial-scale and the experiments more affordable.**

[1] Y. L. Bogomolov, S. F. Lirin, V. E. Semenov, and A. M. Sergeev, JETP Lett. **45**, 680 (1987).
[2] Y. P. Bliokh, J. G. Leopold,. G., Shafir, A. Shlapakovski, Ya. E. Krasik, Phys. Plasmas **24**, 063112 (2017).

Experimental setup for research of mw beam self-channeling in gas and rf plasma

Experimental setups: Self-channeling and SR-BWO HPM source



- SOS based high-voltage generator (**~320 kV, ~5 ns**)
- Magnetically insulated diode for ~2 kA electron beam generation
- Slow wave structure
- Solenoid: **2.5 T, 10 ms**
- Mode converter (**TM_{01}→ TE_{11}**)
- Microwave pulse (**P_{MW} ~ 500 MW, τ ~ 0.5 ns, f ~ 9.7 GHz**)

Gas filled chamber:

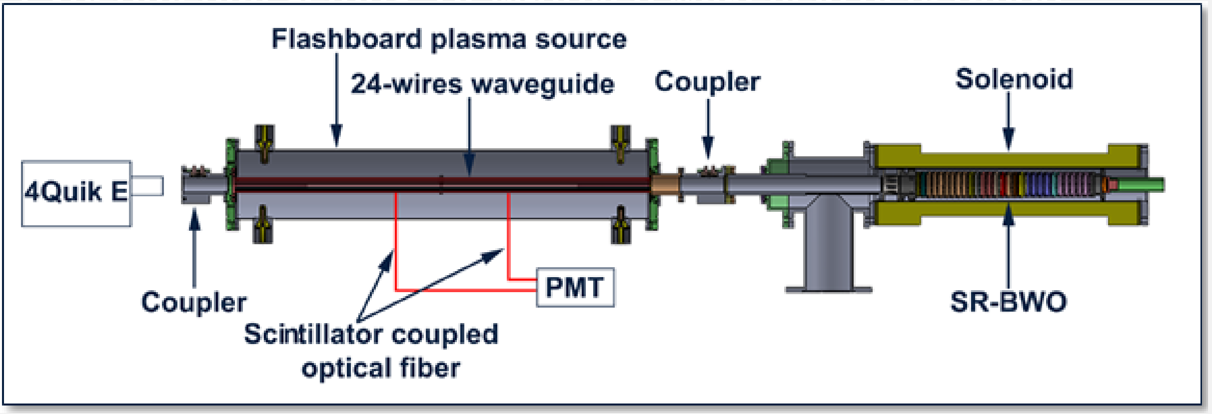
- Gas: air (1—200 Pa),
  He (1 – 500 Pa)

RF plasma chamber:

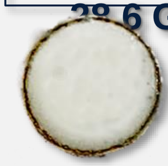
- Plasma density: (1-10)×10^{10}cm^{-3}

Experimental setup for studies of interaction of the mw beam propagating in a waveguide with preliminary formed plasma

Experimental setups: HPM-driven wakefield generation

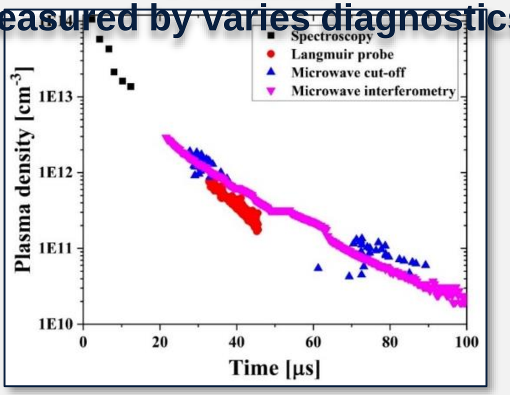


- Microwave source 1: P_{MW} ~ **500 MW, τ ~ 0.5 ns, *f* ~ 9.7 GHz**
- Microwave source 2: P_{MW} ~ **1200 MW, τ ~ 0.8 ns, *f* ~ 28.6 GHz**

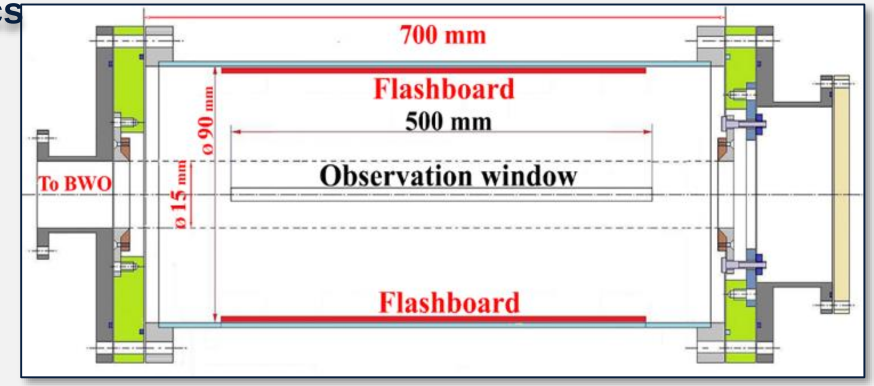


The electron beam pattern on CR-39 target (radius 0.7 cm)

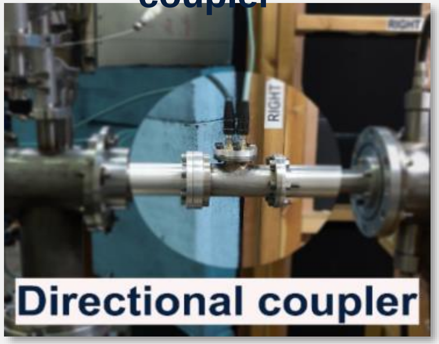
Plasma density temporal evolution measured by varies diagnostics



Experimental chamber with 4 flashboards



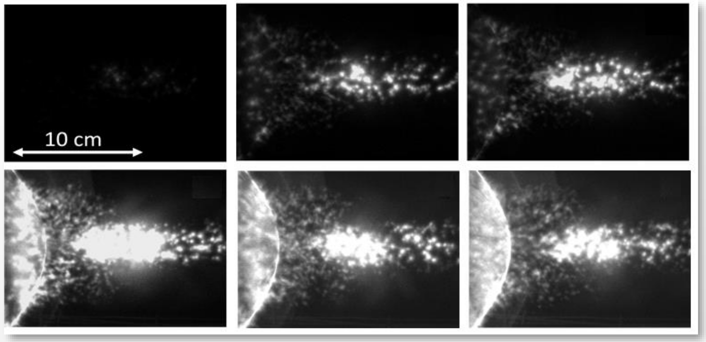
External view of directional coupler



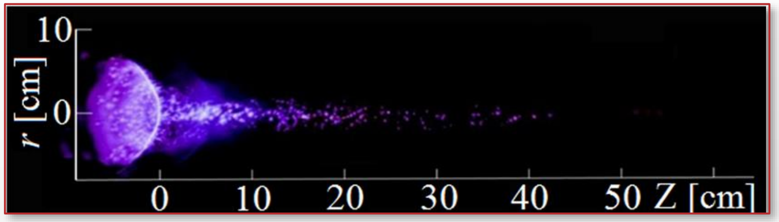
• Microwave pulse self-channeling in gas/plasma

Experimental results of self-channeling in gas

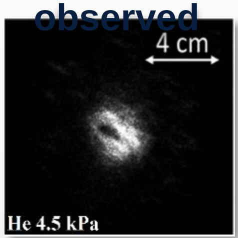
Plasma formation, Air 7 Torr. Time delay of 1 ns between frames each of 1.2 ns duration



Snapshot of ionization channeling



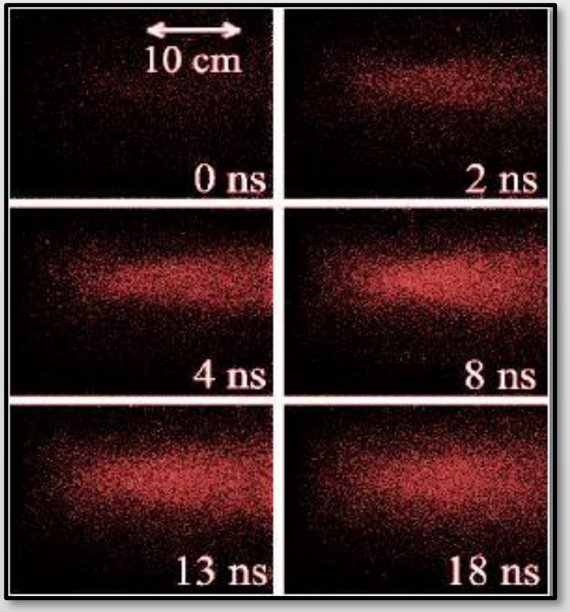
Hollow plasma channel observed



Narrow plasma channel forms with length ~40 cm is ~7 times the Rayleigh length

Experimental results of self-channeling in preliminary formed plasm

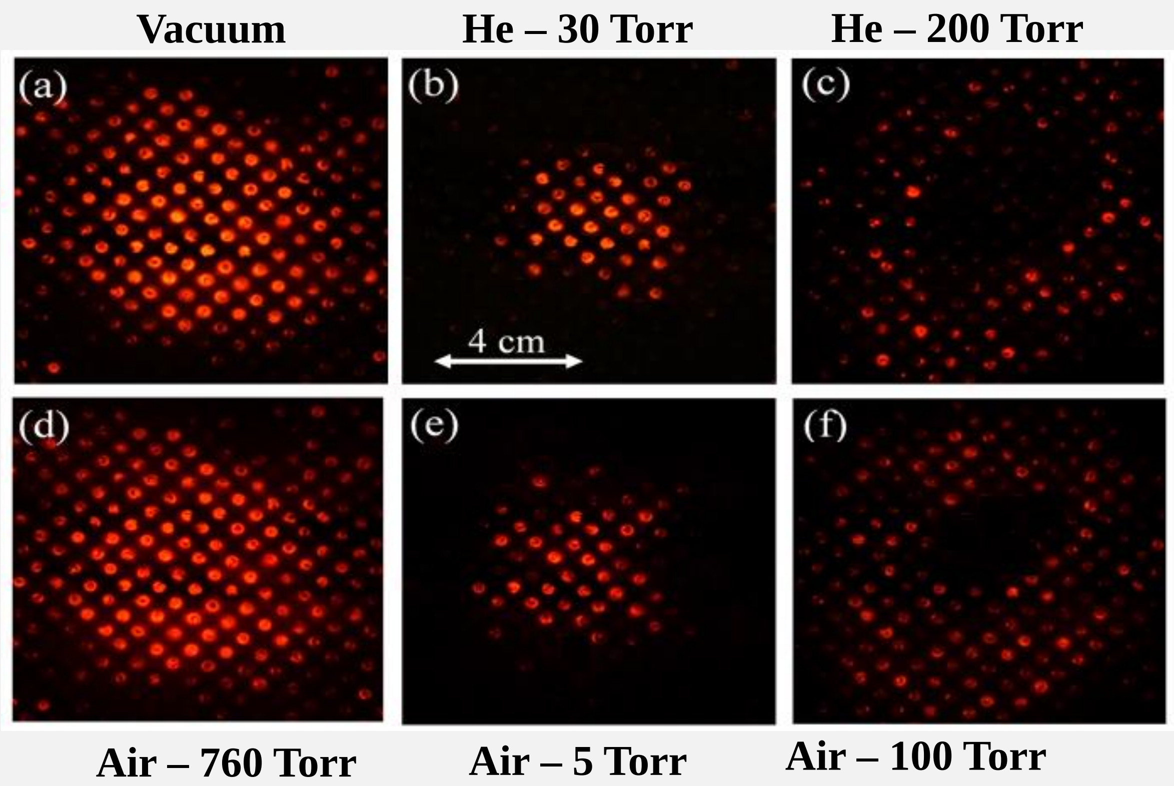
- **Self-channeling in plasma**



Plasma channel formation in preliminary formed Ar plasma, n_e~ 7×10^{10} cm^{-3}, neutral gas pressure ~ 1.5 Pa

- **More than 30 cm long**
- **Radially confined ~5 cm in diameter**
- **6 times longer than the Rayleigh length**

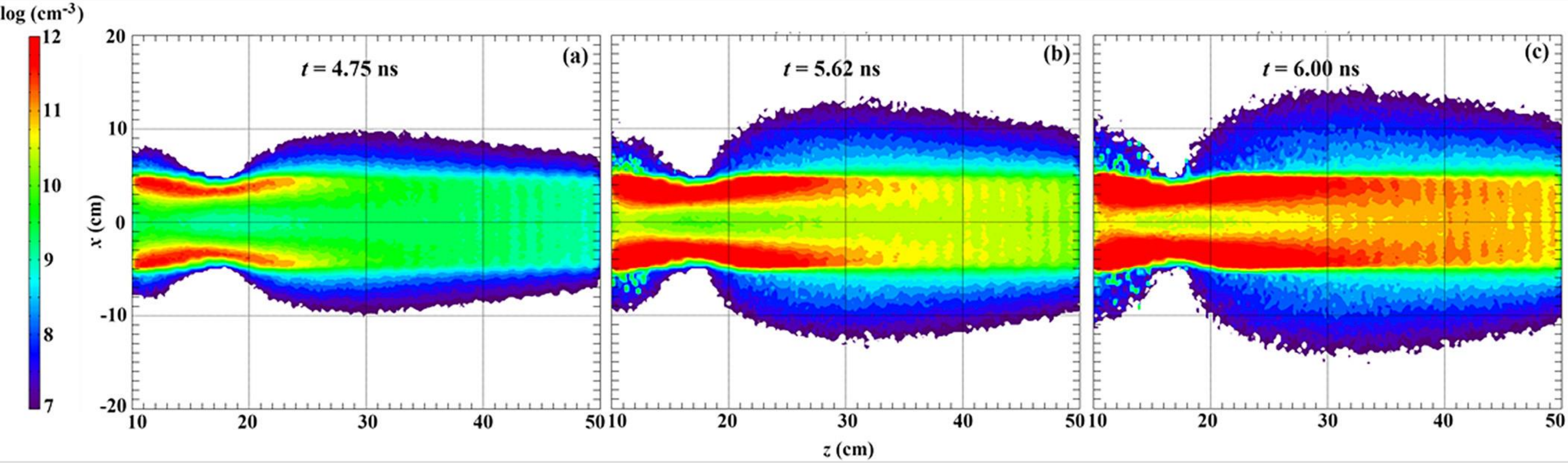
Experimental results – microwave profile



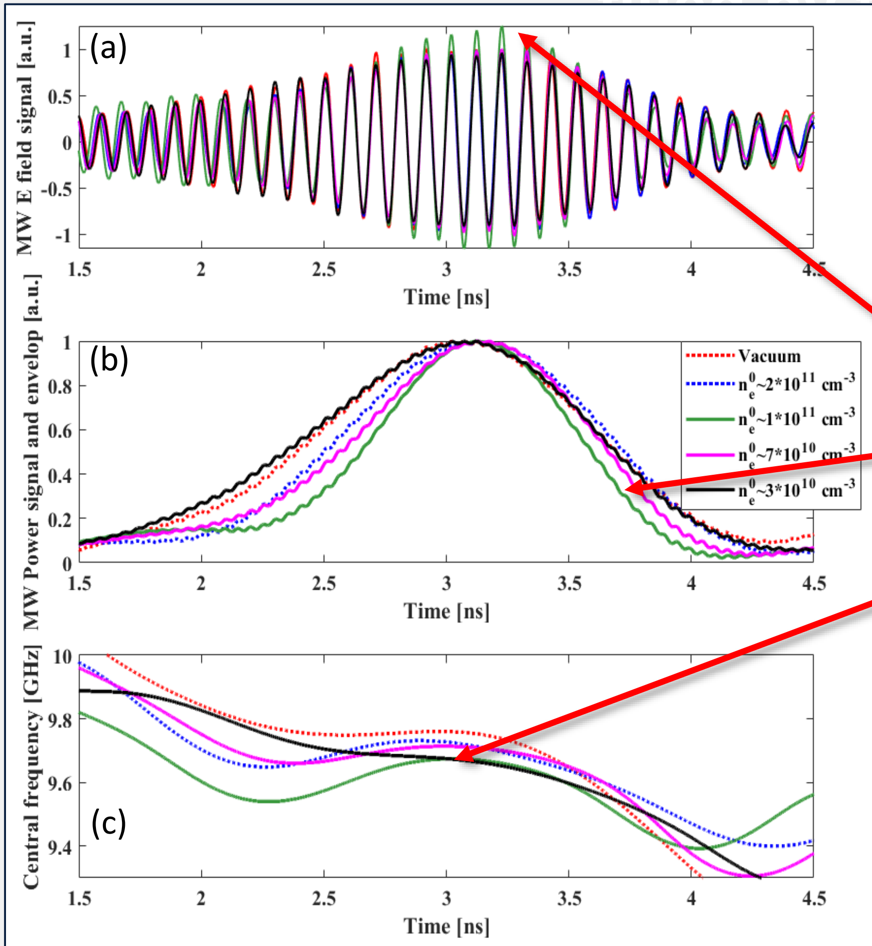
- **30Torr (He)/5Torr (Air) only a central of the mw pulse propagates**
- **200Torr (He)/100Torr (air) only periphery of the mw pulse propagates**

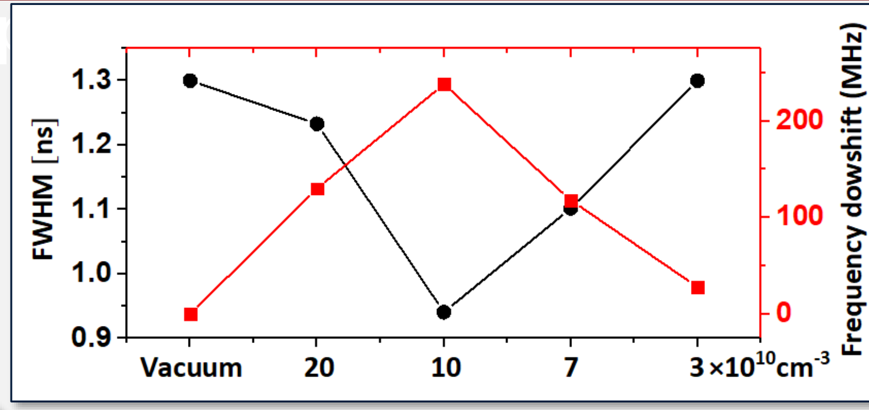
- **Microwave pulse self-channeling in gas/plasma**

LSP™ simulation of ionization self- channeling in (pressure) gases with input MW *P*=400 MW, *τ*=0.4 ns and *f* = 9.7 GHz.



Experimental results of a compression and frequency shift of a mw beam during it propagation within a waveguide

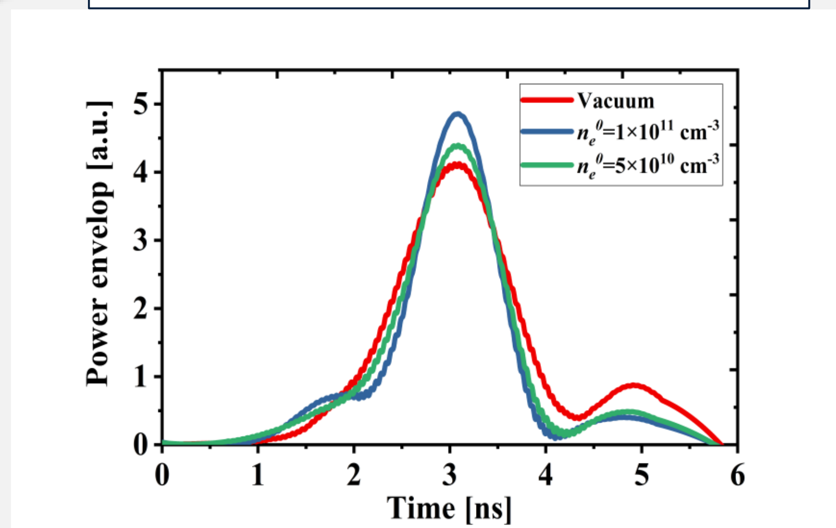




Transmitted MW pulse compression is observed!

The MW frequency downshifts at the rising front of MW pulse is observed!

<u>Transmitted microwave pulse</u> at the exit of the waveguide.
(a) electric field, (b) power; (c) time-frequency spectrum in different preliminary plasma density for the MW pulse: P = 0.4 GW, f = 9.7 GHz

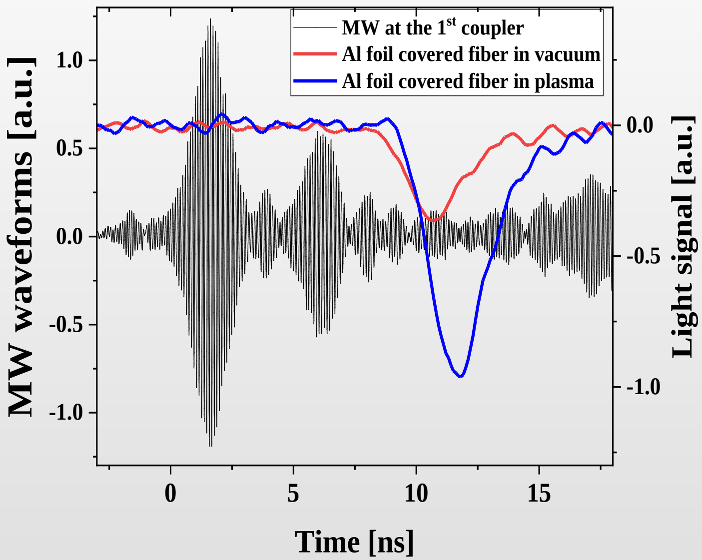


MW power envelop at the exit of flashboard plasma measured by directional coupler

Experimental results: energetic electrons were obtained in radial and axial direction during a mw pulse propagation within a waveguide filled by the plasma

Axially accelerated electrons

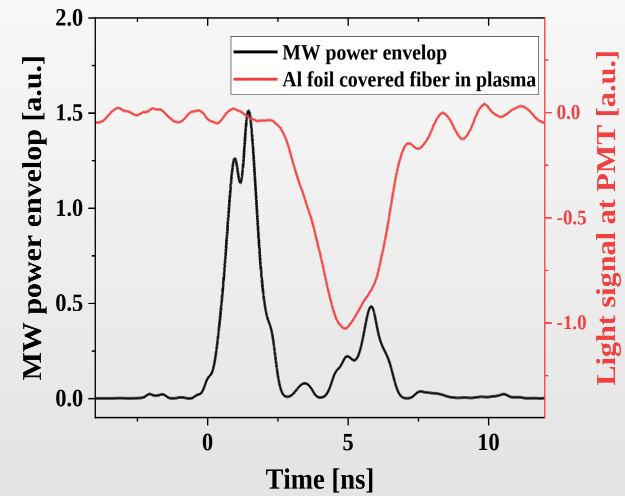
80 μm Al foil



$n_e \sim 5\times10^{10}$ cm^{-3}

Radially accelerated electrons

20 μm Al foil

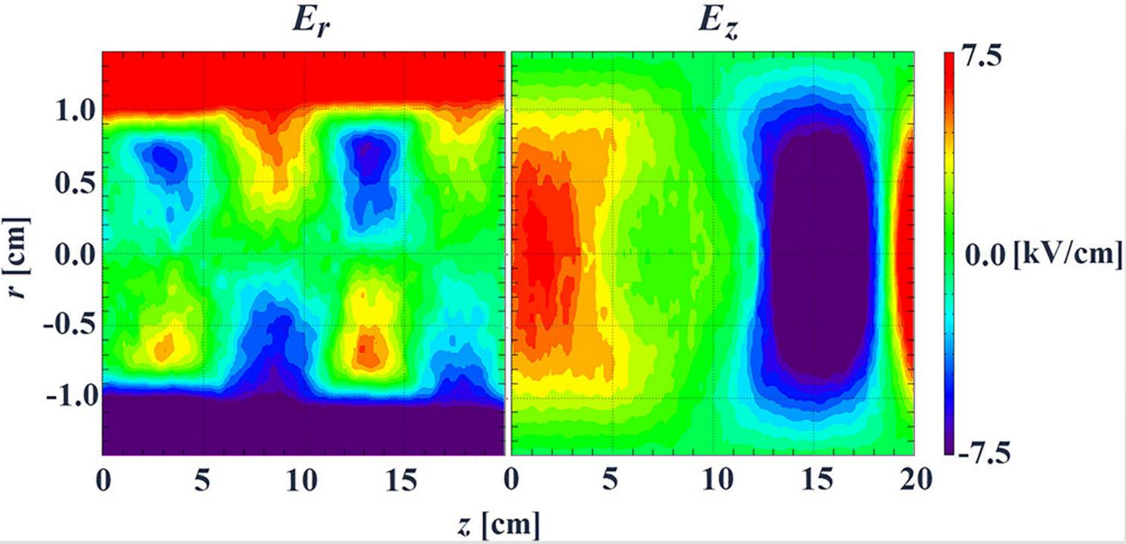


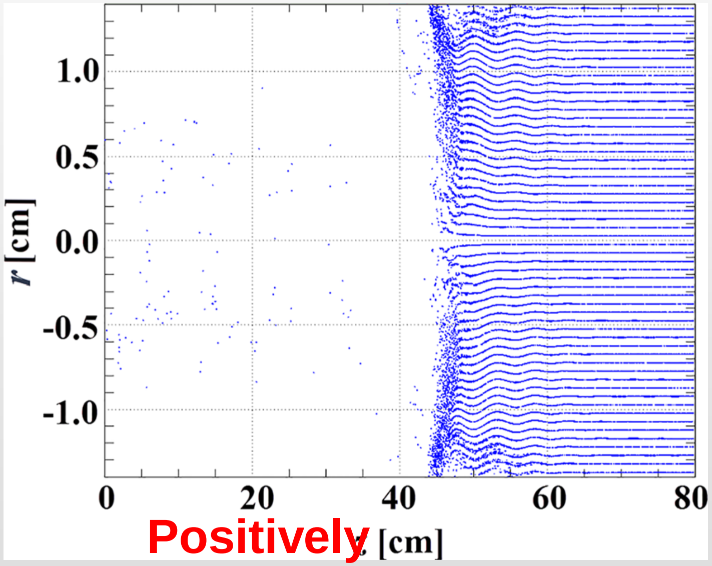
Strong manifestation of a wake-field and positively charged plasma fo

Lsp simulation result of HPM-driven wakefield generation

The (left) side view and (right) front view of LSP™ simulation of mw-driven wake field generation in preliminary plasma n_e=3×10^{10} cm^{-3} with MW pulse power P=500 MW, duration (FWHM) τ=0.4 ns and central frequency f = 9.7 GHz

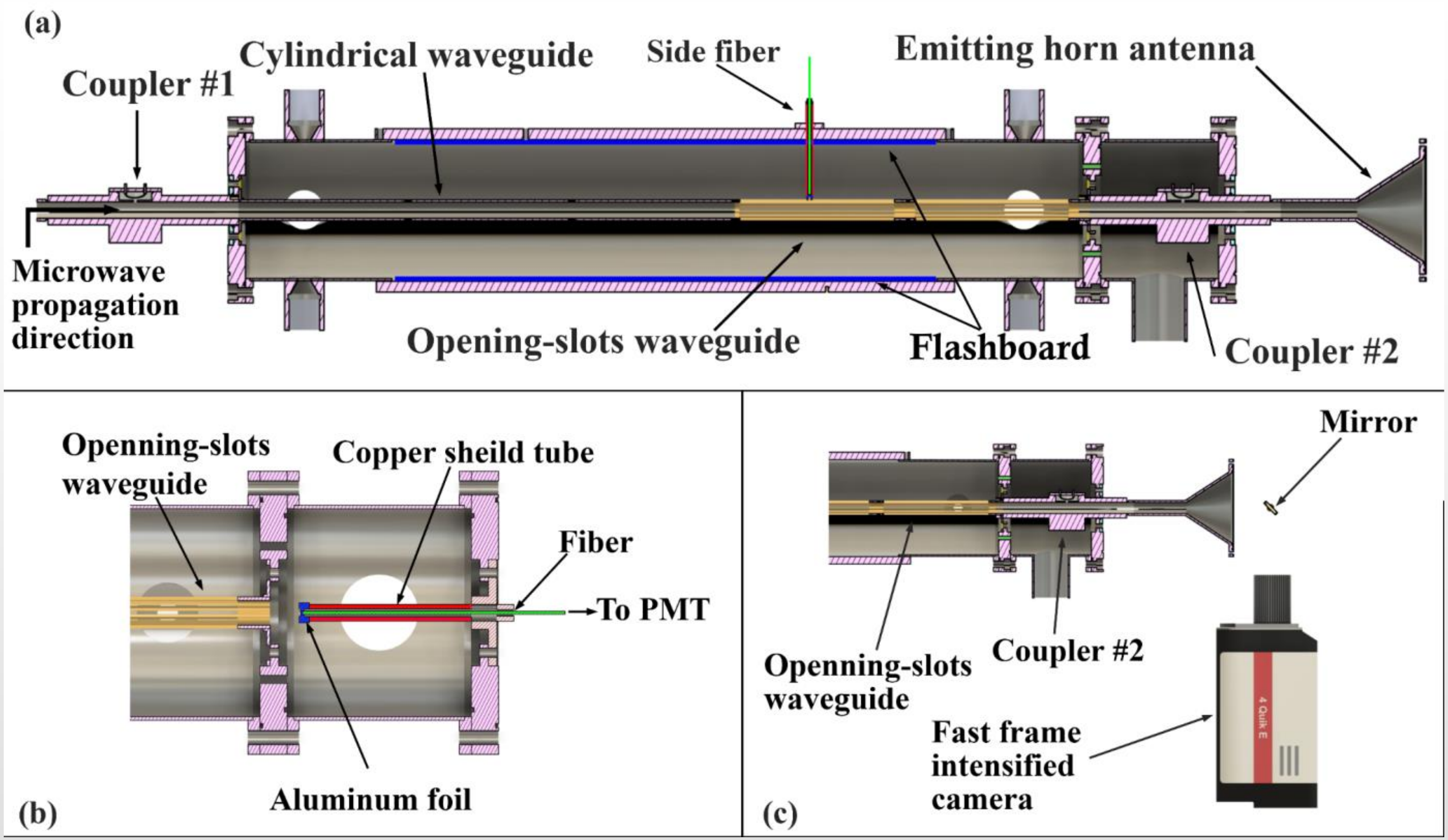
Electron positions in the [r,z] plane within a 1mm thick slice, at t = 3.5 ns for P_{max} = 1.25 GW and n_e=3·10cm^{-3}.





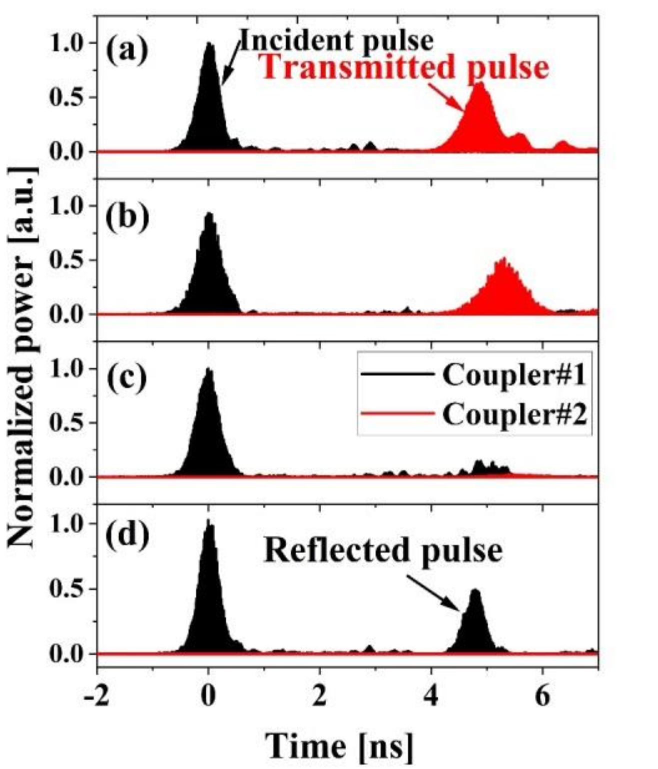
Positively charged plasma

Non-Linear Absorption of HPM Pulses in a Plasma Filled Waveguide

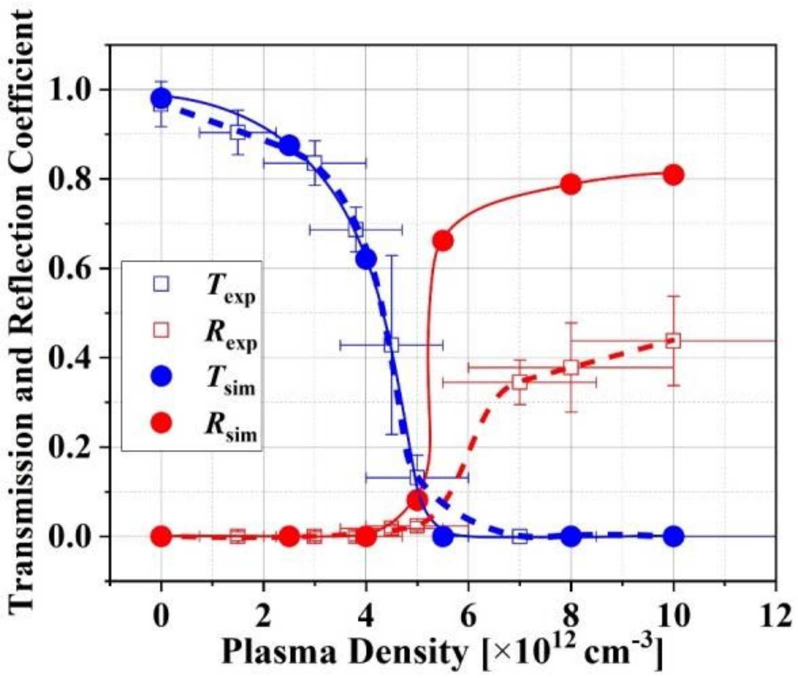


Radial direction: energetic electrons $E_e \sim 70$ keV were observed for $n_e \sim 3\times10^{12}$ cm^{-3}.
Axial direction: energetic electrons $E_e \sim 40$ keV.
Increase in the plasma light intensity lasting >10 ns

Non-Linear Absorption of HPM Pulses in a Plasma Filled Waveguide

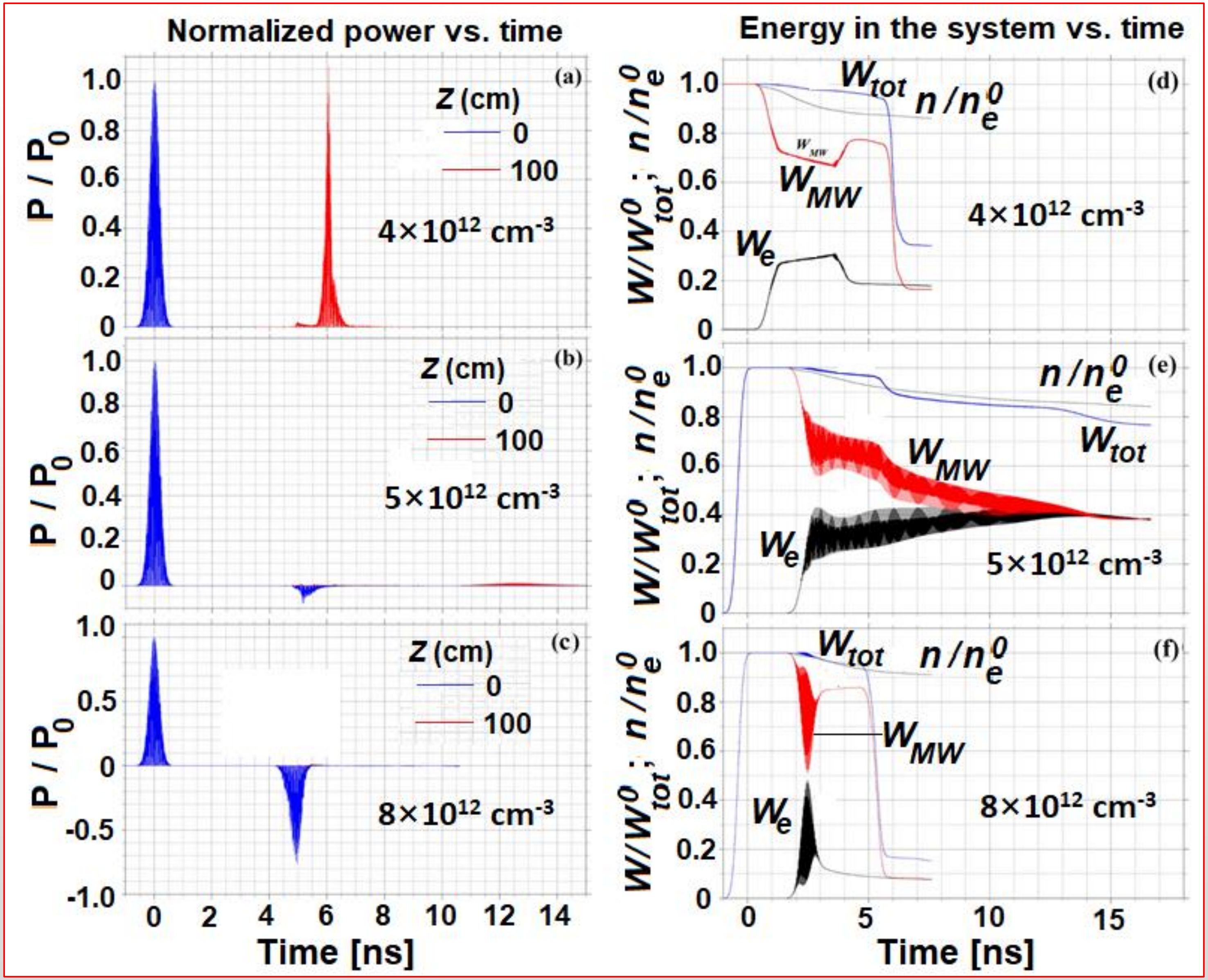


The incident, transmitted and reflected HPM pulse registered in (a) vacuum and at (b) $(3\pm1)\times10^{12}$ cm^{-3}, (c) $(5\pm1)\times10^{12}$ cm^{-3} and (d) $(8\pm1)\times10^{12}$ cm^{-3} plasma densities.



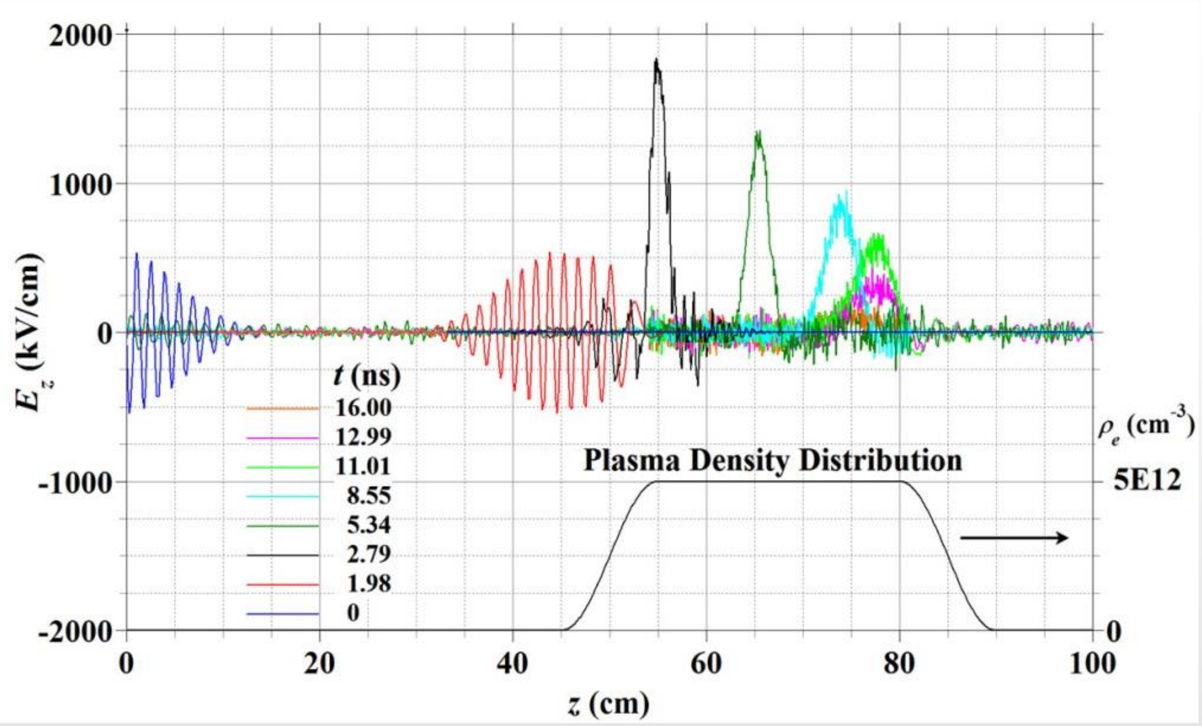
Comparison of the simulated and experimental transmission and reflection coefficients for various plasma densities.

Non-Linear Absorption of HPM Pulses in a Plasma Filled Waveguide



Non-Linear Absorption of HPM Pulses in a Plasma Filled Waveguide

Electric field E_z vs. z ($r = 0$) at various times and the initial plasma density vs. z.



A HPM pulse traversing a plasma filled waveguide, is completely absorbed at a plasma density below the critical density.

The HPM energy transforms into electron kinetic energy through non-linear interaction with the plasma accompanied by loss of part of the electrons to the waveguide walls. This leads to the formation of a positively charged potential well with oscillating electrons. Anomalous HPM pulse absorption occurs when the group velocity of the HPM pulse approaches zero and the pulse has enough time to transfer its energy, due to electron-ion collisions, to the electrons trapped in the well. This non-linear effect does not occur at low power e/m fields and such complete absorption has not been observed before for HPM pulses.

Conclusions

We have so far observed new phenomena:

- Ionization-induced self-channeling in gases and plasma/gas mixtures
- HPM pulse frequency shift and pulse compression
- Complete absorption of the HPM pulse in plasma with density below critical density
- High energy electrons generation
- Formation of positively charged plasma
- HPM-driven wakefield in a cylindrical wave-guide

We expect to observe other phenomena not seen before, using these unique experimental setups